Snowmass2021 - Letter of Interest

Cosmological Parallax: a New Method for Measuring the Geometry of the Universe

Thematic Areas:

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☑ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☑ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Abstract:

The current tension between the expansion rate from Type Ia supernovae (SN) and Baryon acoustic oscillations (BAO) combined with the CMB, and local measurements of H_o has reached the point where a consideration of non-standard cosmographic techniques seems prudent. The deployment of adaptive optics on the next generation of extremely large telescopes (ELTs) will enable the measurement of the positions of astronomical objects (astrometry) with unprecedented precision. For the case of gravitationally lensed sources this will permit a measure of positional changes that result from our secular motion with respect to the Cosmic Microwave Background rest frame (the "Cosmological Parallax"). Its inverse, known as the transverse co-moving distance, is independent of both SN and BAO, is geometrical, and the signal increases with time. A US-ELT program would enable precision astrometry of lensed quasars and galaxies over the entire sky and allow the first measurement of cosmological parallaxes and new, independent constraints on Dark Energy.

Scientific Context:

Despite the enormous success of the SN and BAO constraints[14], there is tension between the inferred value of the Hubble parameter (H_o) and the local, empirical measurements of H_o[2,11]. This discrepancy, > 3σ, has now reached a sufficient level to contemplate that alternative measurements of cosmography are needed. The most common methods of measuring cosmological distances over the past decades[13,4], involve using the luminosity distance (SN) or the angular-size redshift relation (BAO) to infer the distance. By contrast, astronomical parallaxes have been dismissed as a cosmographic measure due to the effect from the Earth's motion around the Sun occurring at the nano-arcsec scales for sources at cosmologically interesting distances[13]. Nevertheless, cosmological parallaxes remain interesting because they constrain the "transverse co-moving distance" and are thus independent from BAO and SN and have a different redshift dependence[8]. Specifically, the parallactic distance (D_p) is:

$D_P = \mathrm{R}(t_0)\frac{D_m}{(1-kD_M^2)^{1/2}}$ where D_M is the transverse co-moving distance:

$$D_M(z) = \frac{D_H}{\sqrt{\Omega_K}} sinh\left[\sqrt{\Omega_K}\frac{D_c(z)}{D_H}\right] \quad \Omega_K > 0,$$
$$D_M(z) = D_c(z) \quad \Omega_K = 0,$$
$$D_M(z) = \frac{D_H}{\sqrt{\Omega_K}} sin\left[\sqrt{\Omega_K}\frac{D_c(z)}{D_H}\right] \quad \Omega_K < 0$$

with $D_H = \frac{c}{H_0}$ and $D_C = \frac{c}{H_0}\int_0^z \frac{dz}{H(z)}$ (the line-of-sight co-moving distance) and with the Friedmann equation[7,5] given by:

$\frac{H^2(z)}{H_0^2} = E(z)$ which for Dark Energy is:

$$E^2 = \Omega_M(1+z)^3 + \Omega_K(1+z)^2 + \Omega_x \exp\left[3\int_0^z \left(1 + w(x) dln(1+x)\right)\right].$$

$E(z)$ can be evaluated for any values of the Dark Energy and cosmological parameters through numerical integration and the cosmological parallax vs redshift (due to Earth's motion around the sun) can be computed to be: 3×10^{-10} arcsec at z = 1 for the standard model. At first glance this effect appears immeasurably small. However, two factors exist that suggest that this is not the full story. First: our 3-d space motion with respect to the CMB is actually 78 AU/year and is known to a few percent[10]. Thus, over ten years the secular parallactic baseline grows to 780 AU. Second: strongly-lensed sources can have angular magnifications as high as 7x[12]. Together, these result in a signal that is ~5,000 times larger than has been traditionally assumed bringing the secular parallactic signal for strongly lensed systems into the few micro-arcsec regime. The astrometric requirements for the next generation of AO-equipped extremely large telescopes is ~ 4 micro-arcsec. It is worth emphasizing that measures of cosmological parallax have a different redshift dependence than either SN or BAO making them both independent and complementary. Specifically, for the luminosity distance (measured via SN) $D_L = (1+z)\, D_M$, for the angular-size distance (measured via BAO) $D_A = (1+z)^{-1} D_M$, and for the transverse co-moving distance (measured via cosmological parallax) $D_P = D_M$[7].

Precision Astrometry via the Next Generation of Extremely Large Telescopes:

Over the next decade, the development of the next generation of large, ground-based telescopes with adaptive optics (such as IRIS on TMT), will provide an imaging resolution of a few milli-arcsec, and hence an astrometric accuracy in the few micro-arcsec regime for a source with sufficiently high signal-to-noise[15]. This is just what is required to measure cosmological secular parallaxes. A sample of approximately 500-1000 strongly lensed galaxy-galaxy systems could be selected from lensed galaxy surveys via DES, LSST, WFIRST and Euclid. Within these systems, we are interested in finding multiple image quasars and lensed galaxies for which the magnifications approach 7x.

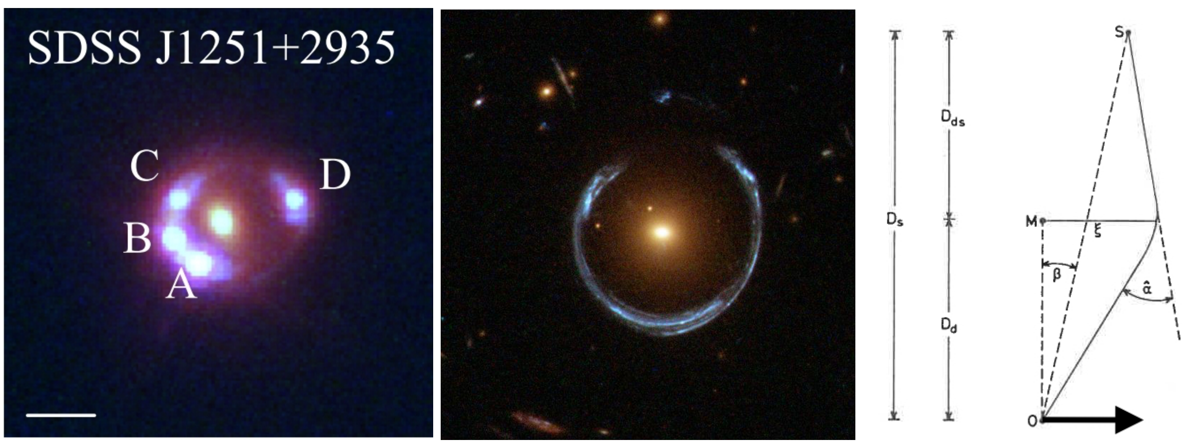

Figure 1: Left: Hubble Space telescope (HST) image of a distant quasar lensed by a foreground galaxy. Middle: HST image of a distant star forming galaxy lensed by a foreground galaxy. Right: Geometry of a forground mass (M) lensing a background source (S). As the observer (O) moves with respect to the CMB the impact parameter (ξ) changes with a corresponding change in the deflection of starlight (α) and in the apparent position of the lensed source.

Prospects and Requirements:

The measurement of cosmological parallax appears feasible. The Rubin Observatory LSST survey will discover thousands of lensed quasars and galaxies[6]. Simple lensing models for multiple-image quasar systems (see Figure 1) suggest that the differential cosmological parallax will be measurable with AO-equipped ELTs enabling the peculiar motions of the lens and source to be constrained along with a measure of the cosmological signal[9]. Fisher matrix modeling implies that astrometry of a sample of ~300 lensed quasar systems over a 10-year baseline would provide constraints on Dark Energy to 5% and a simultaneous constraint on H_0 of 2%. Larger samples or a longer temporal baseline would provide correspondingly tighter constraints. Additional modeling is needed to assess the effect of dark matter halo substructure and microlensing due to stars in the halo of the lensing galaxy. Lensed galaxies may also prove useful given the larger amount of structure in the image. Finally, we propose that a US-ELT system[16] with AO-equipped telescopes in both the Northern and Southern Hemispheres would allow the cosmological parallax signal to be sampled over the entire great circle perpendicular to the CMB vector. A data archive with raw and processed data, calibrations and meta-data would provide a high-value, legacy record of cosmological parallax over 10 or even 50 years since the signal continues to grow with time.

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